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Economic Analysis of an active-yaw control for horizontal-axis small-wind turbines at Alt Empordà

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Abstract. Many horizontal-axis wind turbines of medium and large power systems use active-yaw. However, when small wind turbines are considered, passive yaw is an available solution for most of generators of less than 5kW. In this paper, it is analysed the economic losses of such decisions for the Alt Empordà specific area. Alt Empordà is an interesting harvesting zone because winds resources as *marinada* and *tramontane* are present. In this context, it is necessary the data-wind knowledge at different points of the region. Hence, it is necessary to compute the production for small horizontal-axis generators. Moreover, this work presents developed research for passive-yaw behaviour analysing two different aspects: real acquired data and simulated results. The objective is to compute the lack of electricity production due to the use of passive instead of active-yaw systems.

Key words. Active-yaw control, small horizontal-axis wind turbines, Tramontane wind, Economic Analysis.

1. Introduction

Renewable energy sources play an important role when environmental and economic aspects are considered. Wind energy is a free source of energy that allows power extraction and energy conversion from mechanical to electric power [1]. Wind-turbine generators allow capacities from ten of watts to several megawatts, as well as sizes that have from about 1m to more than 100m. When the mechanical axis of rotation is analysed, horizontal or vertical axis wind turbines are studied [2]. Comparison reports advantages and drawbacks of both systems. Table 1 reports the contrast of some features between both systems.

Table I. – Horizontal vs Vertical axis wind-turbines

	Horizontal	Vertical
Power Coefficient	Higher rise to 0.5	Lower to 0.4
Yaw Control	Required	Not required
Cost	Higher	Lower
Maintenance	Difficult	Easier

Three blades horizontal axis performs much better than vertical axis, especially when aspects such as aerodynamic performance, power coefficient, and wind speed are regarded. Vertical axes have advantages when maintenance, cost, or the no need of yaw mechanism are considered. Analysis of commercial solutions, for small generators (less than 100kV), is done by considering different companies [3]. Some companies as for instance NORVENTO have models with only active yaw [4]. However, other companies, as for instance ENAIR and AEOLOS, report different solutions according to the output power of the generator [5-6].

In this way, ENAIR reports horizontal-axis commercial solutions of three blades of 3kW, 5kW, 10kW, 20kW, and 60kW. 3kW and 5kW wind turbines implement passive yaw systems while the others have active yaw systems. AEOLOS have vertical and horizontal axis wind turbines but when horizontal axis and yaw system are studied, 500W, 1kW, 2kW, and 3kW have passive yaw systems, while 5kW, 10kW, 20kW, 30kW, 50kW, 60kW, and 100kW have active yaw systems.

It can be concluded that when power output of more that 5kW is obtained active yaw system is implemented while for less than 5kW power output passive yaw system is implemented. The reasons of such decisions are mainly economical. This research study the performance of passive versus active systems when power output is near 3kW. The goal is computing the necessary time to amortize an active yaw system.

Active yaw mechanism design for small wind turbines consists of a yaw motor, a reducer, a warm and two-yaw bearing. Active yaw mechanism completes yaw motion in accordance with the instructions of yaw controller [7]. Precise yaw control can yield noticeable power gains [8]. Yaw system designs are still trying to meet the high requirements regarding the lifetime of a wind turbine and turbulent wind loads [9].

Next section presents the features of the available region winds and the area data when to harvest the wind is regarded. Section 3 outlines the research performed in order to measure the lack of energy production due to the use of passive yaw systems. Finally, section 4 presents the conclusion of this research.

2. Energy Wind Resources at Alt Empordà

This section shows the description of the wind resources and the data obtained at Alt Empordà.

A. Main Wind Resources

Marinada and Tramontane are regional wind patterns that significantly influence the available energy resources when Alt Empordà area is analysed. Marinada is a breezy wind; it is a thermal wind that blows during summertime because the difference of temperatures of land and sea areas. Thus, during night, a soft wind from land to sea, blows from warm to temperate areas but during the day the wind blows from sea to land. Normally, the wind speed is less than 20km/h. Recent studies provide a consistent framework for understanding the marinada, paving the way for better modeling and prediction of the phenomenon [10]. The sea breeze is an interesting wind energy resource for micro-generation, not only in the Mediterranean basin but in other areas of the world with similar wind regimes, and particularly in peri-urban coastal areas where large-scale wind farms cannot be implemented. An assessment of the sea breeze energy potential using small wind turbines in peri-urban coastal areas is in [11].

Tramontane is a traditional name for a northern wind. The tramontane in France is a strong, dry cold wind from the north (on the Mediterranean) or from the northwest (in lower Languedoc, Roussillon, Catalonia and the Balearic Islands). It is similar to the mistral in its causes and effects, but it follows a different corridor; the tramontane accelerates as it passes between the Pyrenees and the Massif Central, while the mistral flows down he Rhone Valley between the Alps and the Massif Central [12]. First published studies arise in 1933 from J. M. Jansà, he showed a strong relationship with gradients of pressure and tramontane wind [13]. Developed studies outlined different meteorological situations that can produce tramontane. As instance, strong tramontane happens when Russia and Atlantic Ocean have a strong anticyclone, and Island, U.K. islands, and Mediterranean area have low pressures. The planned field experiment Pyrenean Experiment, (PYREX), is an experimental database obtained from different observations obtained from flights [14]**.** The shelter effect of the Pyrenees was clearly visible in some places. The Tramontane flow model formed as a combination of strong winds and surface heat flux results in the formation of rolls. Using models and acquired data, it is analyzed the speed and orientation of the wind [15]. Results show that higher resolution simulations provide better results in the valleys, but the major improvement obtained by increasing the resolution occurs over the sea. Tramontane is an accelerated and deaccelerated wind. Acceleration is due to the pressure gradient produced by the airflow and the Pyrenees, while deceleration is due to the finish of acceleration and airflow goes inside Mediterranean Sea.

B. Available Wind Resources

This subsection outlines the obtained results concerning different local points of Alt Empordà, see Figure 1. Production arises from the results of the acquired data, from 2019 to 2021. The wind speed data has been statistically analyzed using Weibull distribution to find out wind energy characteristics of Alt Empordà [16]. The following equation shows a Weibull distribution, where λ is a scale or gain and *K* the shape parameter:

$$\boldsymbol{f(x|k|\lambda)} = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(x/\lambda\right)^{k}} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{1}$$

Fig. 1. Wind available data, from meteorological stations and D.O. Empordà, at Alt Empordà

Weibull distributions allow computing the wind density for different points of measure. According to the acquired data, suitable factors for the wind distributions have shape values between 1,263 to 1,538, and scale values between 5,211 and 8,967. Figure 2 depicts the results obtained at Portbou. Using wind-speed histogram and information of different small-wind manufacturers, estimated production can be obtained. For instance, data corresponding to ENAIR 30PRO can be seen in Figure 3. From the obtained information is possible to compute the estimated production of a 3kW aerogenerator and the wind orientation for different locations of Alt Empordà. Table II shows the estimated annual production for a 30PRO ENAIR 3kW wind-generator when the different places are considered.

Table II- Estimated Production case of 3kW aerogenerator

DO Empordà	
Location	Estimated Annual Production
Agullana	80.6 GWh
Masarac	85.3 GWh
Garriguella	83.6 GWh
Port de la Selva	87.4 GWh
Meteorological stations	
Cabanes	10.2 GWh
Navata	14.1 GWh
Portbou	90.3 GWh
Sant Pere Pescador	8.1 GWh
Darnius-Boadella	12.9 GWh

Regarding energy production related to collected data, it is obtained that the majority of DO Empordà locations have larger values of estimated production. One important reason to consider is that meteorological stations normally are placed on urban areas while DO locations are placed on vineyards. In this way, locations play an important role when energy-wind production is pursued.

Figure 4 shows the wind orientation for different places. It is pointed out that for most locations the tramontana and marinada play and important production role. Tramontane is a northern wind, it has an orientation close to 360º, while marinada is an east to west wind or a west to east wind. So, suitable directions of marinada are 90º and 270º. It is noted that places as Portbou, Agullana, Masarac, and Port de la Selva have interesting estimated production values that made suitable to harvest the wind energy.

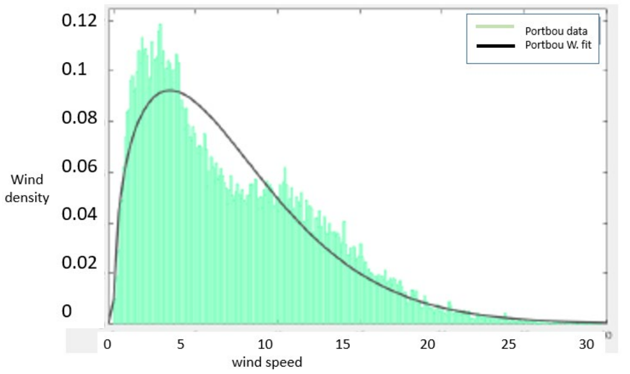

Fig. 2. Wind-speed histogram of Portbou data and the fit using Weibull distribution.

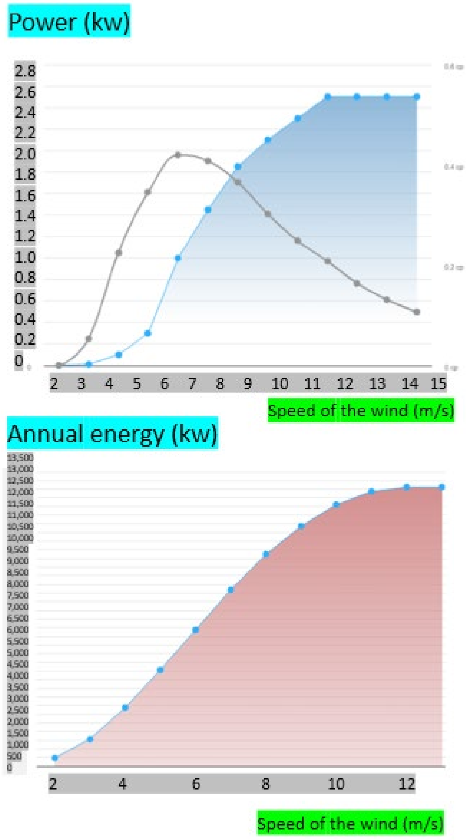

Fig.3. Power and Annual Energy as function of wind speed

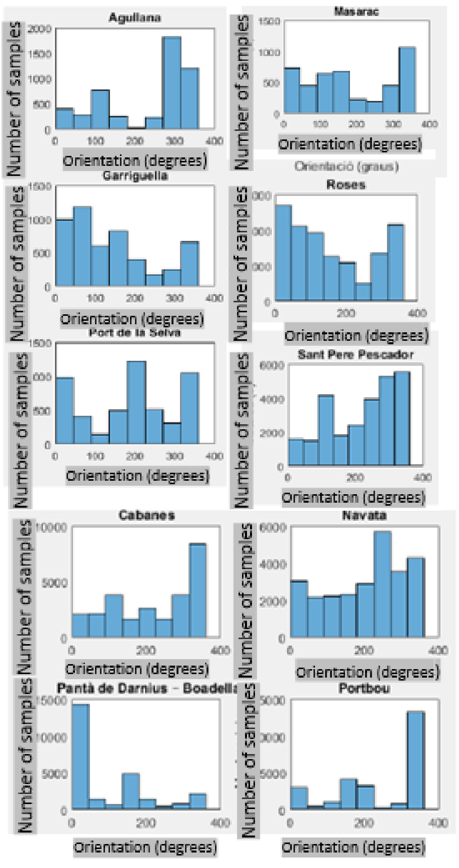

Fig. 4. Wind orientation for the studied locations

3. Computing Losses of Energy Production

This section estimates the losses of production for a 3kW horizontal axis aerogenerator due to the use of a passive yaw mechanism. The research is divided in different subsections that present the experimental data recorded for low-speed wind and strong winds, and the simulated results referred to the generator orientation. Moreover, energy losses are estimated.

A. Low speed winds experimental data

To maximize the production, horizontal axis wind generators must be orientated with the direction of the wind. Figure 5 depicts the two wind components, and how for a wind orientation that don't match the aerogenerator orientation, just a wind component can be considered as productive. In this context, just the wind tangential component acts on a passive yaw system for align the aerogenerator in the direction of the wind. Due to this fact, the tangential component of the wind produces forces on the passive yaw for properly orientate the aerogenerator according to wind direction.

From 2014, it is established a technological collaboration agreement between the University of Girona and the Vilà farm. Figure 6 show experimental data recorded at Eco-granja Vilà during 2023. The analysis of the experimental data reveals that until the wind is not enough strong the nacelle cannot be properly oriented. Thus, for less than 10km/h, 2.8 m/s, the passive yaw is not effective. It is noted that such effects can be emphasized, so just the tangential wind component acts on the passive yaw system. In this way, the angle between the nacelle and the wind should be considered.

From the information of Figure 3, estimation of the losses is carried out. Considering that winds of less than 4 m/s are inefficient because cannot place properly the nacelle, and the wind histogram of Portbou, we estimate near of 1 MWh of losses.

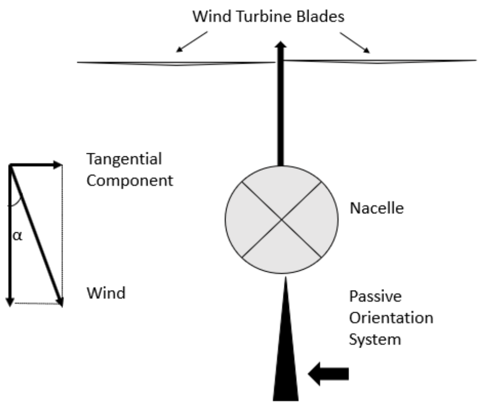

Fig. 5. Wind components, and scheme of an aerogenerator that have a passive yaw system.

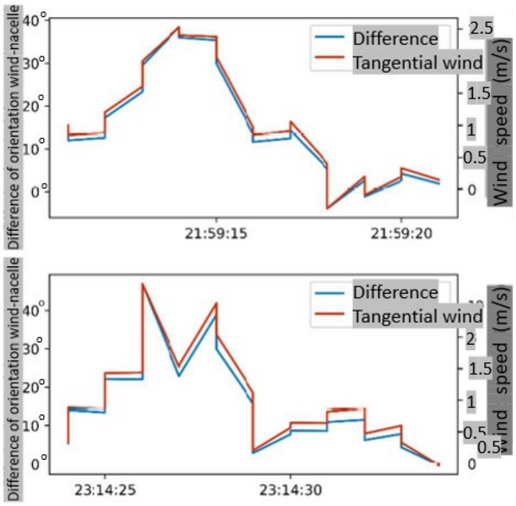

Fig. 6. Experimental data from Eco-granja Vilà.

B. Simulated results

Passive yaw is simulated in this subsection using SIMULINK tool of MATLAB [18]. Passive yaw aligns the nacelle with the wind direction [19]. Modelling the system as:

$$\alpha = \boldsymbol{M}/\boldsymbol{I} \quad (2)$$

Being $\boldsymbol{\alpha}$ the angular position, we can compute the moment of the wind because of kinetic energy:

$$\alpha = \frac{\sum M}{I} = \frac{\rho c_d A d v^2}{2I} \sin\delta + \frac{M_{brake}}{I} \quad (3)$$

Where ρ is the air density, c_d is the aerodynamical coefficient, A represents the passive yaw area, d the distance from the passive yaw to the axis of rotation, v the wind speed, and M_{brake} represents the opposite to movement moments.

Figure 7 shows the simulated model; to compute the moment of inertia, the turbine and wind blades are approximated by a cylinder. Figure 8 depicts the results obtained for a wind of 10 m/s. The output production is represented during the necessary time for alignment. As it is shown, passive yaw behaviour produces oscillations that are decreasing till stability is reached. From analysis of results, it can be concluded that power output can be increased by implementing an active yaw system.

Active yaw system can be done using a DC (direct current) motor, there exist a lot of commercially available solutions. For instance, low-cost actuators with a cost of 50€ can be found at [20]. Hence, it is proposed to use a 12V DC motor, with 30 RPM speed output, and with a torque of 24.5 Nm. With this actuator, an angular acceleration of 1.57 rad/s^2 can be achieved. It can be inferred that with less than two seconds a 30º correction can be achieved. The active yaw can align the system for improving the energy production. It should be highlighted that it is less than a magnitude order when compared with alignment oscillations produced with passive yaw systems.

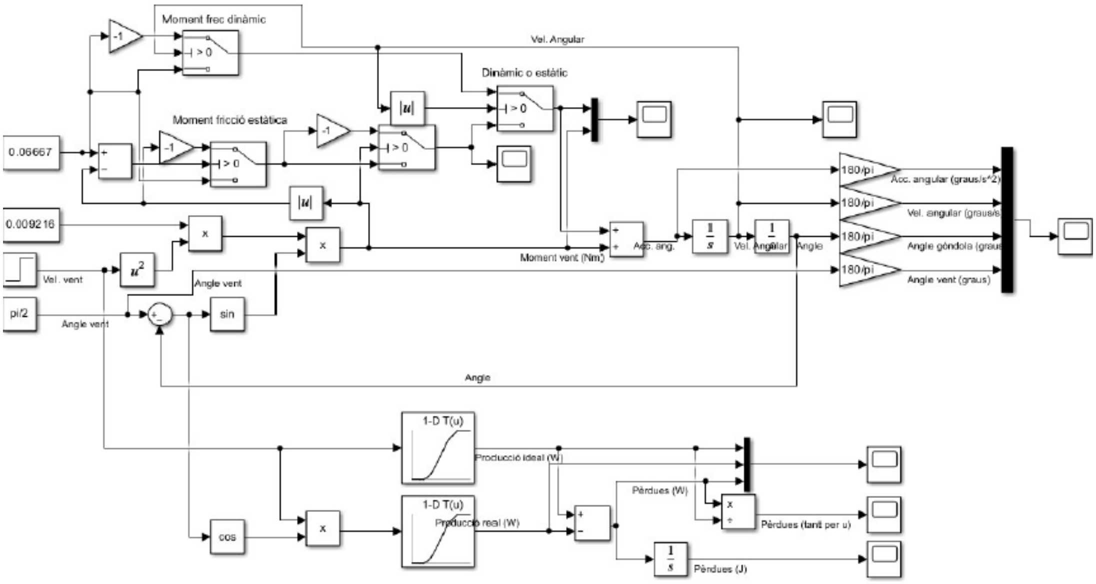

Fig. 7. The simulated model

Tramontane is a turbulent wind where accelerations and decelerations are produced. Moreover, according to the profile of wind orientations for the different locations, tramontane wind is an important productive wind. For these reasons, next subsection outlines experimental data about the tramontana wind that allow to compute the economic analysis under such wind.

C. Northern winds experimental observations

Using the information of section 2, we compute northern wind importance for the locations analysed. In this way, table III represents northern wind percentage when referred to the total wind recourses.

Once again, we point that location of meteorological station may be not appropriate to place an aerogenerator. Despite this, the importance of Tramontane, as northern wind, is highlighted. Table III shows averaged percentage values between 52% and 41%. It means that near 50% of available resources are due to northern winds.

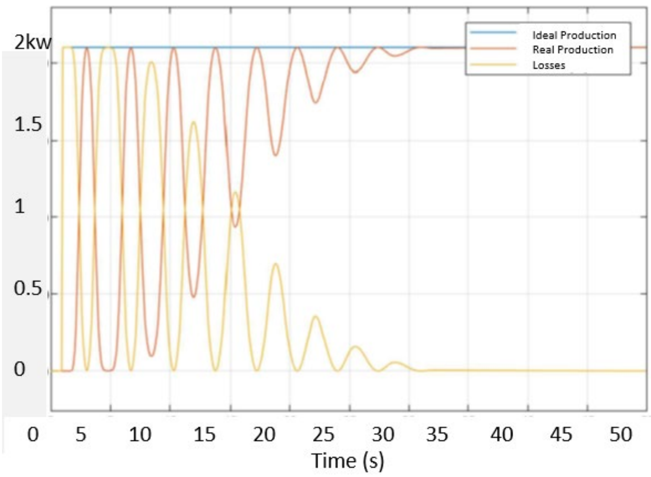

Fig. 8. Passive system of orientation under a wind of 10 m/s.

Table III.- Northern wind percentage at analysed locations

DO locations	
Location	Percentage
Agullana	Between 65% and 30%
Masarac	Between 54% and 44%
Garriguella	Between 40% and 34%
Port de la Selva	Between 46% and 40%
Meteorological stations	
Cabanes	Between 43% and 36%
Navata	Between 34% and 27%
Portbou	Between 66% and 63%
Sant Pere Pescador	Between 49% and 28%
Darnius-Boadella	Between 72% and 67%

Regarding the results obtained, two aspects should be noted:

- Orientation of 0 degrees is considered as northern due to the discontinuity value between 0 and 360º.
- Due to the turbulence of Tramontane, some other orientation values can be produced. However, in this work, only northern wind orientations are considered.

Meteorological stations use minutes as acquisition units. However, regarding Tramontane wind, the following aspects should be known:

- As is considered a turbulent wind, changes on orientation may happen and should be reported.
- Acceleration a deacceleration also should be considered.

When wind orientation is analysed, northwest, north and northeast winds are all called as Tramontana wind by the people. Typically wind orientation moves from northwest to north, and from north to northeast. Regarding the duration of Tramontana episodes, the length is from three to four days. Due to climate change, periods of a week or even more are infrequent. Normally, Tramontana winds have gusts that are two or three times the wind speed averages. Gusts are produced near two times each minute and can achieve values of three times the averaged wind speed.

Table IV shows the data acquired from the experimental results in which seconds are used as unit of time. Table IV outlines averaged sampled values obtained during autumn and winter of 2024.

Table IV.- Averaged experimental tramontane data, 2024

Gust duration in seconds	4
Constant wind duration in seconds	22
Wind gust speed (m/s)	28
Wind speed average (m/s)	13
Gust orientation (degrees)	90

According to the experimental data acquired, Tramontane turbulences and gusts are present and may change the orientation significantly. Moreover, Wind orientation for the studied locations reported on section two and three show a significant relevance of winds with north component when aerogenerators production is considered. Economic analysis of active yaw can be performed. In this way, considering a 30% of improvement and a 40% of the power resources associated to the tramontana, we estimate an extra annual production of more than 7MWh each year.

4. Conclusion

The economic analysis of an active-yaw control for horizontal-axis small-wind turbines at Alt Empordà concludes their feasibility for power output of near 2kW.
Based on results presented, simulation results show that when changes in wind orientation happen, then power output present oscillations for near half minute (see Figure 8). Due to the nature of Tramontana wind, it is experimentally reported that orientation changes may occurs near two times each minute. Thus, using the area available wind resources where Tramontana play an important role, the use of active-yawn control systems is proposed.

In this way, the following aspects can be concluded:

- The location of the aerogenerator is very important. The place should be sensitive to northern wind, but also to west and east winds.
- Amortization of an active yaw system can be achieved when effective active systems are used.
- Active yaw control performance is a main aspect to be considered. It is assumed proper functioning but is a subject of nowadays research.

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